

# THE UBIQUITOUS RADIO CONTINUUM EMISSION FROM THE MOST MASSIVE EARLY-TYPE GALAXIES

MICHAEL J. I. BROWN<sup>1</sup>, BUELL T. JANNUZI<sup>2</sup>, DAVID J. E. FLOYD<sup>3</sup>, JEREMY R. MOULD<sup>3,4</sup>

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## ABSTRACT

We have measured the radio continuum emission of 396 early-type galaxies brighter than  $K = 9$ , using 1.4 GHz imagery from the NRAO VLA Sky Survey, Green Bank 300-ft Telescope and 64-m Parkes Radio Telescope. For  $M_K < -24$  early-type galaxies, the distribution of radio powers at fixed absolute magnitude spans 4 orders of magnitude and the median radio power is proportional to  $K$ -band luminosity to the power  $2.78 \pm 0.16$ . The measured flux densities of  $M_K < -25.5$  early-type galaxies are greater than zero in all cases. It is thus highly likely that the most massive galaxies always host an active galactic nucleus or have recently undergone star formation.

*Subject headings:* galaxies: elliptical and lenticular, cD — galaxies: active — radio continuum: galaxies

## 1. INTRODUCTION

The most massive early-type galaxies reside within dark matter halos with masses of  $10^{13} M_\odot$  or more (e.g., Brown et al. 2008). One may expect the gas within these dark matter halos to radiatively cool, gravitationally collapse and form stars (e.g., White & Rees 1978). In contrast to this expectation, stellar population synthesis modeling reveals that the bulk of the stars in very massive galaxies formed  $\simeq 10$  Gyr ago, with relatively little star formation since (e.g., Tinsley 1968; Trager et al. 2000). While some early-type galaxies harbor cold gas, the most massive galaxies are typically bathed in plasma with temperatures on the order of millions of Kelvin (e.g., Canizares et al. 1987). What is heating the plasma and regulating star formation in very massive galaxies has yet to be robustly identified.

In the recent literature, a popular mechanism for heating the plasma is the injection of energy from an active galactic nucleus (AGN feedback; e.g., Tabor & Binney 1993; Croton et al. 2006). While a quasar could heat the gas within its host galaxy (e.g., Hopkins et al. 2006), powerful quasars are so rare that they probably cannot be responsible for the lack of star formation in nearby massive galaxies. For nearby galaxies, it is more plausible that low luminosity AGNs (with a high duty cycle) are heating the plasma. Bubbles in the distribution of X-ray emitting gas surrounding nearby radio galaxies correspond to the locations of radio lobes (e.g., Fabian et al. 2003; McNamara et al. 2000). The dissipation of shocks and sound waves resulting from the production of these bubbles and jets may inject sufficient energy into the plasma to offset radiative cooling (Fabian et al. 2003).

Radio observations provide insights into the plausibility and nature of AGN feedback. We may expect to observe radio emission from all massive galaxies, resulting from star formation and/or AGNs. Radio emission is associated with the cavities in the X-ray emitting plasma produced by AGNs and radio emission results from recent star formation (Condon

1992). However, in isolation, the presence of radio emission from massive galaxies is not proof of AGN regulation of star formation. For example, AGNs with low power jets (e.g., Baldi & Capetti 2009) may have little impact on the surrounding plasma. If there are massive galaxies without radio emission, this may indicate that brief bursts of AGN activity are sufficient to truncate star formation (e.g., Hopkins et al. 2006). Alternatively, a mechanism other than AGN feedback may be heating the plasma surrounding galaxies (e.g., Birnboim & Dekel 2003).

Previous studies show that  $\sim 30\%$  of the most massive galaxies are radio continuum sources (e.g., Fabbiano et al. 1989; Sadler et al. 1989; Wrobel & Heeschen 1991; Best et al. 2005; Shabala et al. 2008). These studies matched optical and radio source catalogs, which limits the sample to radio sources that meet conservative signal-to-noise criteria, so catalogs are not swamped by noise. (Even when conservative criteria are applied, the tail of the noise distribution may produce spurious sources.) Recent studies have generally utilized large redshift surveys that exclude the nearest galaxies, and thus miss radio sources fainter than  $10^{22} \text{ W Hz}^{-1}$ . Consequently, the faint radio emission from nearby early-type galaxies has not been completely characterized by the prior literature.

In this letter we present a study of the 1.4 GHz radio emission from  $K < 9$  early-type galaxies. The choice of 1.4 GHz is pragmatic, as it allows us to utilize existing NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and single-dish imagery. We assume the radio emission is the consequence of either recent star formation or an AGN. If this assumption holds, our conclusions do not depend on which emission process is dominant in these galaxies (i.e., synchrotron, free-free). Rather than match our early-type galaxies to radio source catalogs alone, we also measure flux densities from radio images. We can thus include significant (albeit noisy) information on the radio flux densities of early-type galaxies that would have otherwise been excluded from our study. This allows us to characterize the very faint radio emission from the most massive early-type galaxies.

## 2. THE SAMPLE

Our parent sample is the 2MASS Extended Source Catalog (Jarrett et al. 2000), from which we select objects with apparent magnitude  $K < 9$  (dust corrected; Schlegel et al. 1998),

<sup>1</sup> School of Physics, Monash University, Clayton, Victoria 3800, Australia

<sup>2</sup> National Optical Astronomy Observatory, Tucson, AZ 85726-6732, USA

<sup>3</sup> School of Physics, University of Melbourne, Parkville, Victoria 3010, Australia

<sup>4</sup> Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Melbourne, Victoria 3122, Australia

declination  $\delta > -40^\circ$  and galactic latitude of  $|b| > 15^\circ$ . Of the 1107 objects selected with these criteria, 979 have morphologies available from the Third Reference Catalog of Bright Galaxies (de Vaucouleurs et al. 1991) while virtually all of the remaining objects are Galactic.

Our principal sample is the 400 galaxies that are classified as elliptical or lenticular galaxies in the RC3 (with T type classifications of -1 or less). Many of these galaxies have redshifts in the RC3 catalog, while the remainder have redshifts provided by Falco et al. (1999), Huchra et al. (1999), Wegner et al. (2003), Jones et al. (2009) and the NASA Extragalactic Database. For 170 galaxies we have redshift independent distances from Extragalactic Distance Database (Tully et al. 2009), while for the remaining galaxies we use a Hubble constant of  $73 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (Spergel et al. 2007). The luminosity distances of the galaxies span from 0.7 to  $10^2 \text{ Mpc}$ .

Our principal radio imaging is the 1.4 GHz NRAO VLA Sky Survey (Condon et al. 1998), which has an angular resolution of  $45''$  and an RMS noise of  $\simeq 0.45 \text{ mJy}$ . As the NVSS can underestimate the flux densities of powerful and extended radio sources, we also measure flux densities using lower resolution ( $\sim 12''$ ) imaging from the 300-ft Green Bank and the 64-m Parkes radio telescopes (Condon & Broderick 1985, 1986; Barnes et al. 2001, Calabretta in prep.).

We employed the following method to measure flux densities for each galaxy. At the 2MASS position of each galaxy we measured a flux density per beam directly from the NVSS images. For those galaxies with a flux density per beam greater than  $2 \text{ mJy}$ , we searched for the nearest counterpart in the NVSS catalog within  $2'$  and used the NVSS catalog deconvolved flux density. To account for powerful extended sources, we measured the flux density per beam using Green Bank 300-ft and Parkes single dish data, and utilized this flux density measurement if it was greater than  $0.6 \text{ Jy}$ . If the flux density per beam measured with single dish imagery was greater than  $5 \text{ Jy}$ , we utilized the integrated flux density rather than the flux density per beam.

Our flux density measurements are imperfect, but our principal conclusions remain unchanged unless gross systematic errors are present. To verify that our data was free of such errors, we visually inspected the radio imagery and compared our flux densities with those from the literature. Visual inspection also revealed that few galaxies in our sample are extended Fanaroff & Riley (1974) class II radio sources. The flux densities of 4 galaxies neighboring bright radio sources could not be reliably measured, and excluding these galaxies reduced our final sample to 396 early-type galaxies. The properties of the sample galaxies are summarized in Table 1.

### 3. THE RADIO FLUX DENSITY AND LUMINOSITY DISTRIBUTIONS

The 1.4 GHz flux densities of the 396  $K < 9$  early-type galaxies are plotted as a function of  $K$ -band absolute magnitude in Figure 1. For the lowest mass galaxies, with  $M_K \sim -22.5$ , only a small fraction have counterparts in the NVSS catalogs and most galaxies have flux densities consistent with zero plus a random measurement error. In contrast, all 59 of the  $M_K < -25.5$  early-type galaxies (corresponding to stellar masses of  $\gtrsim 2.5 \times 10^{11} M_\odot$ ) have measured flux densities greater than zero and just two of the  $61 -25.0 < M_K < -25.5$  early-type galaxies have measured flux densities below zero. As random errors will result in measured flux densities scattered above and below the true flux densities, it is highly likely

that all  $M_K < -25.5$  early-type galaxies in our sample are radio continuum sources, with flux densities of  $\gtrsim 1 \text{ mJy}$ .

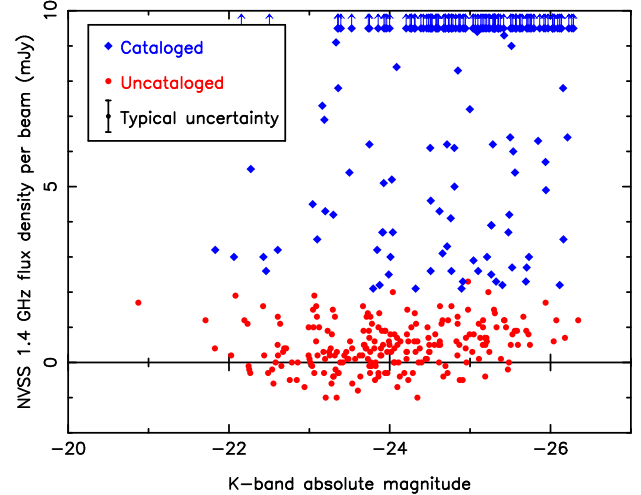


FIG. 1.— The flux densities of early-type galaxies as a function of  $K$ -band absolute magnitude. For the lowest mass galaxies, relatively few galaxies have counterparts in the NVSS catalogs and most galaxies have flux densities consistent with zero plus a random measurement error. Galaxies with  $M_K < -25.5$  (corresponding to stellar masses of  $> 2 \times 10^{11} M_\odot$ ) have counterparts in the NVSS catalogs or flux densities greater than zero. As random errors will broaden the flux density distribution, it is likely that all  $M_K < -25.5$  early-type galaxies in our sample are radio continuum sources with flux densities of  $\gtrsim 1 \text{ mJy}$ .

In Figure 2 we present the radio power of early-type galaxies as a function of  $K$ -band absolute magnitude. As noted by others (e.g., Fabbiano et al. 1989; Sadler et al. 1989), the radio powers of early-type galaxies are a strong function of absolute magnitude. Although our  $K = 9$  magnitude limit excludes some extremely powerful radio sources (e.g., Cygnus A), the radio power of  $M_K < -24$  galaxies at fixed  $K$ -band magnitude (or stellar mass) still spans 4 orders of magnitude. The most massive galaxies can have 1.4 GHz powers as large as that of M 87 ( $\simeq 7 \times 10^{24} \text{ W Hz}^{-1}$ ) or less than the Milky Way ( $\simeq 4 \times 10^{21} \text{ W Hz}^{-1}$ ).

To model the distribution of radio powers,  $P_{1.4}$ , we have utilized a log-normal probability density function where

$$\rho(P_{1.4}; \mu, \sigma) = \frac{1}{P_{1.4}\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln P_{1.4} - \mu)^2}{2\sigma^2}\right] \quad (1)$$

$$\mu = \ln\left[\alpha\left(\frac{L_K}{10^{11}L_\odot}\right)^\beta\right] \quad (2)$$

$$\sigma = \gamma\mu \quad (3)$$

where  $L_K$  is the  $K$ -band luminosity and  $\alpha$ ,  $\beta$  and  $\gamma$  are free parameters. This parameterization is empirical (i.e., lacks physical motivation) but, as discussed below, provides a good description of the observed distribution of radio powers as a function of  $L_K$ . If the radio emission from early-type galaxies was a function of  $L_K$  and time only, then this parameterization would directly measure the radio duty cycle of early-type galaxies. However, the radio emission from early-type galaxies is a function of environment (host halo mass and location within a halo; e.g., Best et al. 2007; Wake et al. 2008;

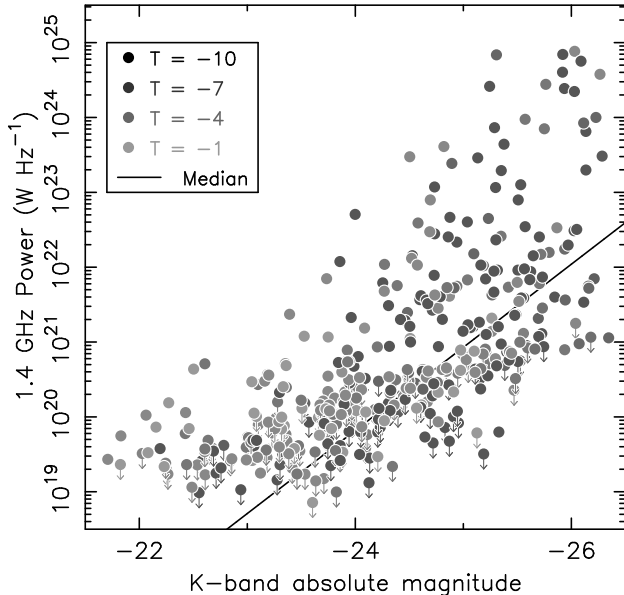


FIG. 2.— The 1.4 GHz radio power of early-type galaxies as a function of  $K$ -band absolute magnitude. The data are color coded by RC3  $T$  type and for sources with measured flux densities less than  $2\sigma$  above zero, we plot  $2\sigma$  upper limits. At a fixed absolute magnitude, the distribution of radio powers spans four orders of magnitude for early-type galaxies brighter than  $M_K = -24$ . The median radio power of early-type galaxies (derived from fitting a log-normal probability density function to the data) is proportional to  $K$ -band luminosity to the power of  $2.78 \pm 0.16$ .

Mandelbaum et al. 2009), so this parameterization constrains rather than measures the duty cycle. The integral of the probability density function provides an estimate of the fraction of galaxies with luminosity  $L_K$  that have radio powers above (or below) a particular threshold, and this can be compared with estimates from the prior literature (e.g., Best et al. 2005). The radio luminosity function can be derived by convolving the probability density function with the  $K$ -band luminosity function of early-type galaxies.

We used our model of the distribution of radio powers and an empirical model of the NVSS flux density measurement errors to determine the likelihood of a particular galaxy (with known luminosity distance and  $M_K$ ) having a particular measured flux density. Our model of the NVSS flux density measurement errors is the distribution of flux densities measured in each pixel of the NVSS, so we account for the non-Gaussian error distribution and source confusion. We then used the maximum likelihood method to determine the best-fit values and uncertainties for our model of the radio powers of early-type galaxies. All galaxies were used when fitting the model, irrespective of their measured flux densities. However,  $M_K > -23$  galaxies provide limited constraints on the model parameters so our conclusions principally apply to  $M_K < -23$  early-type galaxies. Our best-fit values for the log-normal distribution parameters  $\alpha$ ,  $\beta$  and  $\gamma$  are  $1.16 \pm 0.20 \times 10^{20} \text{ W Hz}^{-1}$ ,  $2.78 \pm 0.17$  and  $6.62 \pm 0.29 \times 10^{-2}$  respectively.

To verify our model, we have used it to generate 500 realizations of the anticipated observed properties of our sample, and four of these “mock catalogs” are plotted in Figure 3. 2D Kolmogorov-Smirnov (KS) tests (Peacock 1983) run on the mocks and the original sample show that the our model is

consistent with the observed distribution of radio powers. We also used the mocks to test the assumption that the measured minimum flux density is an underestimate of the true minimum flux density for  $M_K < -25.5$  early-type galaxies (due to random errors broadening the measured flux density distribution). For 96% of the mock catalogs, the measured minimum 1.4 GHz flux density is less than the true minimum 1.4 GHz flux density for  $M_K < -25.5$  early-type galaxies. It is thus highly likely that all  $M_K < -25.5$  early-type galaxies are radio continuum sources.

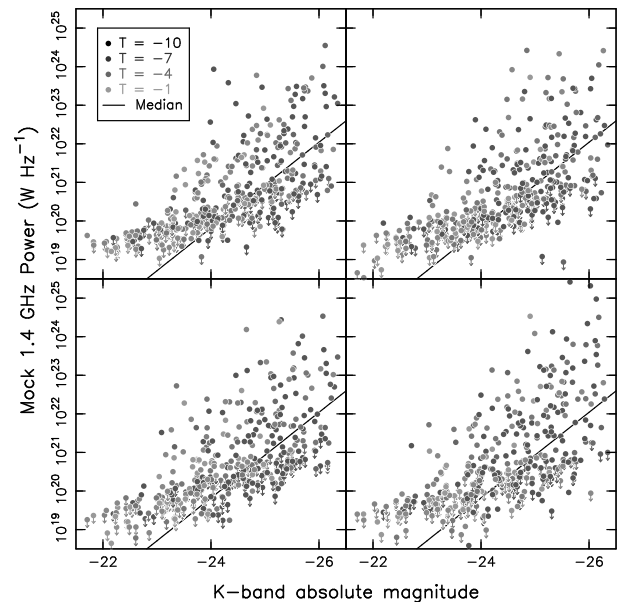


FIG. 3.— The radio powers of early-type galaxies as a function of  $K$ -band absolute magnitude for four mock catalogs. The distribution of radio powers approximates what is seen in Figure 2. Apparent features are seen in the real and mock catalogs, but these are not significant departures from our model of the distribution of radio powers.

The median 1.4 GHz radio power of early-type galaxies is proportional to  $K$ -band luminosity to the power of  $2.78 \pm 0.17$ . For comparison, Fabbiano et al. (1989) and Sadler et al. (1989) find 5 GHz radio power is proportional to  $B$ -band luminosity to the power of  $2.36 \pm 0.37$  and  $2.2 \pm 0.3$  respectively. As these studies use  $B$ -band and 5 GHz imagery, the modest differences between these results and our own may arise from the different wavelengths used. The fraction of early-type galaxies hosting a radio source more powerful than  $10^{23} \text{ W Hz}^{-1}$  is roughly proportional to  $L_K^{2.2}$ , increasing from 0.2% at  $M_K = -23.5$  to 26% at  $M_K = -26$ , in good agreement with Mauch & Sadler (2007). The observed trend also agrees well with the radio-loud fraction as a function of stellar mass derived by Best et al. (2005), if  $M_K = -26$  corresponds to a stellar mass of  $\simeq 4 \times 10^{11} M_\odot$  (e.g., Bell & de Jong 2001). As the relationship between radio power and  $K$ -band absolute magnitude is extremely steep and the mass function of galaxies has an exponential cut-off at high masses, the most luminous radio sources will be hosted by galaxies spanning a relatively small range of  $K$ -band absolute magnitude.

The distribution of radio powers at fixed  $K$ -band absolute magnitude is extremely broad, spanning approximately 4 or

ders of magnitude. A consequence of this is that stacking of radio sources will converge slower towards the mean or median value than one would expect for a narrower Gaussian distribution of radio powers. A stack of 100 early-type galaxies will result in an estimate of the mean radio power that is accurate to only  $\simeq 20\%$ , even if individual galaxies are detected with high signal-to-noise.

While it is beyond the scope of this letter to explore all the possibilities that could influence radio power, we can briefly explore some of the obvious options. At a given  $K$ -band absolute magnitude, there is no clear correlation between radio power and morphological type in Figure 2, and this conclusion is consistent with previous studies of early-type galaxies (e.g., Wrobel & Heeschen 1991). For  $M_K < -25$  early-type galaxies, the average RC3 T types of galaxies that are above and below the median radio power differ by just 0.6. More subtle correlations between morphology (including transitory features) and radio power may only be revealed by high resolution imaging of early-type galaxies (e.g., de Ruiter et al. 2005).

While others have explored the correlations between radio power and environment (e.g., dark matter halo mass) in detail, two galaxies in our sample illustrate that any correlation between environment and radio power is likely to have considerable scatter. Coma cluster galaxies NGC 4874 and NGC 4889 (the brightest cluster galaxy) both have  $M_K \simeq -26.2$  and RC3 T Types of -4, but their 1.4 GHz flux densities are 724 mJy and 1 mJy respectively. This large difference in radio flux density for two otherwise similar galaxies suggests that the radio powers of early-type galaxies may vary by roughly than 3 orders of magnitude over long periods of time.

#### 4. WEAK RADIO SOURCES IN EARLY-TYPE GALAXIES

We have previously concluded that all  $M_K < -25.5$  early-type galaxies are probably radio sources, as their measured flux densities are greater than zero. To verify the presence of weak radio sources in massive galaxies, we have stacked NVSS images of the 16  $M_K < -25.5$  early-type galaxies without counterparts in the NVSS catalogs. For comparison, we have also stacked images of the 119  $M_K > -24$  early-type galaxies without counterparts in the NVSS catalogs. As we show in Figure 4, a 0.9 mJy source is present in the stack of massive galaxies while radio emission is only marginally detected in the stack of lower mass galaxies. This is not unexpected, as the median radio power of early-type galaxies is an extremely strong function  $K$ -band absolute magnitude. The radio continuum emission from  $M_K < -25.5$  early-type galaxies indicates that they are rarely (perhaps never) truly passive, as the vast majority harbor an AGN or have recently ( $\lesssim 100$  Myr) undergone star formation.

The most powerful radio sources in our sample are clearly AGNs, but the weakest radio sources could result from star formation. Star formation is known to produce  $10^{21}$  W Hz $^{-1}$  of radio emission in some early-type galaxies (Wrobel & Heeschen 1988), which would result from just  $\sim 1 M_\odot$ /yr of star formation (Bell 2003). However, there are weak arguments for AGNs being responsible for the broad distribution of observed radio powers for  $M_K < -25.5$  early-type galaxies. The radio emission in the stacked images is compact, as one may expect from low luminosity AGNs, although the NVSS beam is  $45''$  wide. Slee et al. (1994) found parsec-sized radio cores in 70% of early-type galaxies, even when the total radio power was only  $10^{22}$  W Hz $^{-1}$ . If radio emission is being produced by multiple mechanisms, one

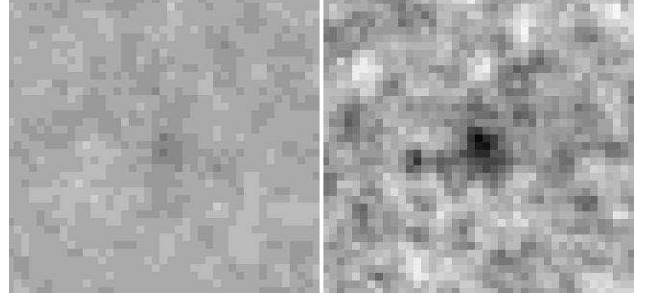


FIG. 4.— Median stacks of early-type galaxies with  $M_K > -24$  (left) and  $M_K < -25.5$  (right) without counterparts in the NVSS catalogs. The images are  $10'$  on a side, the pixel scale is  $15''$ , white corresponds to  $-0.5$  mJy and black corresponds to 1 mJy. While little radio emission is detected from the low mass galaxies, the stack of high mass galaxies has a flux density of 0.9 mJy.

may expect an obvious superposition of multiple distributions. This should be the case for X-ray emission from early-type galaxies (e.g., Fabbiano et al. 1989), but we do not see this in the radio in Figure 2. However, these are not definitive arguments for the presence of radio AGNs in all massive galaxies and further observations are required. Inconsistencies between star formation rates derived from observations at radio and other wavelengths (e.g., mid-IR) may identify the weakest AGNs in early-type galaxies. Alternatively, AGNs may be identified using source sizes and brightness temperatures determined with high frequency and high resolution radio imaging.

#### 5. SUMMARY

We have measured the 1.4 GHz radio continuum emission from  $K < 9$  early-type galaxies, utilizing archival imagery from the NVSS, Green Bank 300-ft Telescope and 64-m Parkes Radio Telescope. The distribution of radio powers at fixed absolute magnitude spans 4 orders of magnitude for  $M_K < -24$  early-type galaxies, and the median radio power is proportional to  $K$ -band luminosity to the power  $2.78 \pm 0.16$ . Our analysis is not restricted to galaxies with high signal-to-noise radio detections, and the distribution of noisy flux density measurements provides important constraints on the radio emission from early-type galaxies. Relatively few low mass early-type galaxies are detected with high signal-to-noise, and the flux density measurements for the remaining objects are scattered around zero. In contrast, most  $M_K < -25.5$  early-type galaxies have robust detections, and the remaining galaxies consistently have flux density measurements greater than zero. As random measurement errors will broaden the measured distribution of flux densities, it is highly likely that all massive galaxies are radio continuum sources. If this is the case, all  $M_K < 25.5$  early-type galaxies harbor an active galactic nucleus or have recently undergone star formation.

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TABLE 1  
THE  $K < 9$  EARLY-TYPE GALAXY SAMPLE (COMPLETE TABLE IS AVAILABLE ONLINE)

Name	J2000 Coordinates	2MASS $m_K$ (Dust corrected)	RC3 T Type	$S_{1.4}$ (mJy)	$d_L$ (Mpc)	$M_K$	$P_{1.4}^a$ (W Hz $^{-1}$ )
NGC 16	00:09:04.300 +27:43:46.03	8.76	-3.0	$-1.0 \pm 0.5$	42	-24.34	-
NGC 50	00:14:44.555 -07:20:42.38	8.66	-3.0	$22 \pm 1$	75	-25.72	$1.5 \times 10^{22}$
NGC 57	00:15:30.873 +17:19:42.22	8.65	-5.0	$0.9 \pm 0.5$	74	-25.70	$< 1.2 \times 10^{21}$
NGC 80	00:21:10.865 +22:21:26.11	8.90	-2.5	$0.9 \pm 0.5$	78	-25.56	$< 1.3 \times 10^{21}$
NGC 128	00:29:15.070 +02:51:50.57	8.51	-2.0	$1.5 \pm 0.5$	58	-25.30	$6.0 \times 10^{20}$
NGC 205	00:40:22.075 +41:41:07.08	5.56	-5.0	$0.1 \pm 0.5$	0.8	-18.84	$< 6.9 \times 10^{16}$
NGC 221	00:42:41.825 +40:51:54.61	5.05	-6.0	$0.7 \pm 0.5$	0.8	-19.50	$< 1.3 \times 10^{17}$
NGC 315	00:57:48.916 +30:21:08.33	7.93	-4.0	$1.8 \pm 0.1 \times 10^3$	68	-26.23	$1.0 \times 10^{24}$
NGC 383	01:07:24.939 +32:24:45.20	8.46	-3.0	$4.8 \pm 0.2 \times 10^3$	70	-25.76	$2.8 \times 10^{24}$
NGC 410	01:10:58.872 +33:09:07.30	8.36	-4.0	$5.8 \pm 0.5$	73	-25.94	$3.6 \times 10^{21}$
NGC 439	01:13:47.251 -31:44:50.09	8.68	-3.3	$21 \pm 1$	79	-25.79	$1.6 \times 10^{22}$
NGC 474	01:20:06.696 +03:24:54.97	8.54	-2.0	$0.3 \pm 0.5$	32	-23.97	$< 1.5 \times 10^{20}$
NGC 499	01:23:11.459 +33:27:36.30	8.71	-2.5	$0.7 \pm 0.5$	60	-25.18	$< 6.9 \times 10^{20}$
NGC 507	01:23:39.950 +33:15:22.22	8.28	-2.0	$62 \pm 2$	67	-25.87	$3.4 \times 10^{22}$
NGC 524	01:24:47.707 +09:32:19.65	7.13	-1.0	$3.1 \pm 0.4$	24	-24.77	$2.1 \times 10^{20}$
NGC 533	01:25:31.432 +01:45:33.57	8.43	-5.0	$29 \pm 1$	76	-25.97	$2.0 \times 10^{22}$
NGC 547	01:26:00.577 -01:20:42.43	8.48	-5.0	$5.9 \pm 0.5 \times 10^3$	76	-25.92	$4.0 \times 10^{24}$
NGC 584	01:31:20.755 -06:52:05.02	7.29	-5.0	$0.6 \pm 0.5$	20	-24.23	$< 7.3 \times 10^{19}$
NGC 596	01:32:51.906 -07:01:53.54	7.96	-4.0	$0.1 \pm 0.5$	22	-23.73	$< 5.7 \times 10^{19}$
NGC 636	01:39:06.529 -07:30:45.37	8.43	-5.0	$-0.3 \pm 0.5$	30	-23.94	$< 6.4 \times 10^{19}$

<sup>a</sup> When the flux density is within  $2\sigma$  of zero, a  $2\sigma$  upper limit for the radio power is provided.